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4

Knowledge and Understanding of the Natural World

Major Findings in the Chapter:

- *Children's intuitive concepts of the natural world can be both resources and barriers to emerging understanding. These concepts can be enriched and transformed by appropriate classroom experiences.*
- *Changes in a student's knowledge do not necessarily follow a linear improvement across grades, and an individual's understanding can vary across contexts.*
- *Conceptual development can occur in many different ways. Some kinds of conceptual change occur naturally as a consequence of the child's everyday experiences, whereas others require intentional effort, often by both a learner and a teacher.*
- *Major changes in conceptual frameworks are often difficult to make because they require learners to break out of their familiar frame and reorganize a body of knowledge, often in ways that draw on unfamiliar ideas. Such changes are facilitated by instruction that helps students construct an understanding of the new concepts, and provides opportunities for them to strengthen their understanding of the new ideas through extended application and argumentation.*

In this chapter we summarize research related to Strand 1: know, use, and interpret scientific knowledge of the natural world. We begin with a discussion of how children's knowledge develops as they move through the K-8 years. We consider each of the knowledge domains identified in Chapter 3—physics, biology, psychology, chemistry, and earth sciences—and sketch

out how early understanding is extended and revised. In the second half of the chapter, we describe the process of conceptual change, considering the various ways changes can occur and how they can be facilitated.

CHANGES IN CONCEPTUAL UNDERSTANDING DURING THE K-8 YEARS

There is no magic line that divides children's cognitive development before entering elementary school from their cognitive development after the onset of formal schooling. Children continue to refine their abilities to use information at various levels of abstraction and become ever more sophisticated at understanding the nature of good explanations, methods of inquiry, and the role of evidence. They also show substantial increases in the ability to explicitly talk about patterns and principles and realize their relevance across a wider and wider range of settings. In addition, they greatly expand their understandings of pathways to knowledge and how to navigate pathways in ways that exploit the greater expertise of specialists in various areas. All of these patterns of change during the elementary school years have their roots in preschool and earlier, but in many cases the changes greatly accelerate in older children. Explicit instruction and educational experiences in school and other settings clearly help foster many of these changes, but others should be understood as the continuation of processes that started long before school and that now also interact with those of formal education.

In this section we very briefly provide examples of how children's knowledge changes over the K-8 years, building on the knowledge they develop prior to school. We highlight three main ideas. First, there are some (positive) improvements in children's understanding (e.g., increased knowledge, increased understanding of some mechanisms, increased understanding of relations among variables). Second, not all changes necessarily bring children closer to canonical scientific views. For example, children bring naïve conceptions about the natural world that differ from accepted scientific explanation (often referred to as misconceptions). Some of the naïve concepts are persistent and difficult to change. Others are transitory and appear to resolve themselves with time and experience. Third, there is considerable variability in the changes that occur. An individual's understanding can vary across contexts. There is also variation among children when they attain certain understandings. This variation is likely to reflect differences in the kinds of previous educational opportunities or experiences they have had. The latter findings underscore that these changes do not just come for free with increasing age.

It is important to emphasize that changes in knowledge during this period do not necessarily follow a pattern of linear improvement across

grades (Siegler, 1998). Instead, there are many twists and turns and misconceptions that develop along the way. In fact, growth can be difficult to gauge, as it sometime follows a U-shaped pattern, with apparent regressions or intermediate constructions developing as part of the process. In this context, misconceptions or wrong ideas are not necessarily a bad thing, nor are they necessarily a sign of a deeply held systematic alternative theory—some are highly context dependent and even quite transitory. However, they do reflect deeper conceptual difficulties, and understanding the *reasons* for those difficulties can be instructive. In some cases, misconceptions develop in part because of limited symbolic tools available to students or limitations in conceptual knowledge in other domains (e.g., having mathematics based on natural rather than rational number, having limitations in geometric understandings).

Some misconceptions may stem from alternative *ontological* commitments that constrain children's ideas. If children assume that an entity or relation belongs to a fundamentally different kind of thing, that assumption can derail attempts to link up their conceptual system with that of adults or older children. For example, if fire is thought of as a kind of stuff rather than a symptom of an event (combustion), that misattribution of fire to the wrong category (a substance instead of an event) can lead to dramatically different inferences about other properties of fires. More broadly, conceptual change may be more difficult when the child's naïve conception assigns entities in a domain to a different ontological category than an adult's conception assigns them (Chi, 2005). In contrast, if a young child initially misconceives an entity as a different sort of thing but in the same ontological category, then conceptual change may be much easier to achieve (Chi, 2005). For example, a child might initially think that germs are like small insects inside the body instead of knowing that they are a different kind of organism, but such a mistake makes the same ontological commitments and would be relatively easy for a child to surmount.

Multiple factors contribute to the changes described in this section. Thus, we need to avoid the trap of looking for a single explanation for such diverse phenomena. Instead, we need to identify the range of important factors and explore how they contribute and interact with one another. Many of these factors may be primarily experiential in nature (rather than maturational in a strict biological sense), and there are a variety of ways that experience can contribute to growth. Even in the case of more maturationally based factors (such as increases in working memory, processing speed, capacity for attention, self-regulation, executive function), there is evidence for interactions with experiential factors in these developments as well. For example, many factors (knowledge, processing speed, strategies) affect measured short-term storage span of memory, and, although measured short-term storage span increases with age, many argue that short-term storage

capacity is not changing with age. In both children and adults, richer knowledge bases result in larger memory capacities (Chi, 1978). There is more evidence, however, for an underlying maturational component for changes in processing speed (although some aspects are also clearly affected by experience) (Kail, 1991; Luna et al., 2004; Travis, 1998).

Extending and Changing Understandings of Naïve Physics

Children's understanding of the simple mechanics of bounded objects undergoes considerable change during the elementary school years. One area of dramatic change concerns an appreciation of how to interrelate variables that are concerned with trajectories, most notably, distance, speed, and duration. Many years ago, the Swiss psychologist, Jean Piaget, demonstrated confusions among these variables in young children (Piaget, 1946a, 1946b; Piaget and Inhelder, 1948), but only recently have more systematic studies documented the ways in which children come to make sense of each of these variables and their interrelations. Those studies now suggest that even young preschool children distinguish distance, speed, and time in some contexts (in contrast to Piaget's claim that these notions are initially completely undifferentiated) (Acredelo, Adams, and Schmid, 1984; Matsuda, 1994, 2001; Wilkening, 1981). Some of the differences across tasks depend on what criteria children use in judging each task. Many of the tasks require them to use qualitative criteria (e.g., comparing starting and stopping times); some give them direct information in some symbolic form and examine their ability to integrate it (a clock that says 10 versus 20 seconds; a distance strip; two animals that are known to be fast or slow, like turtles and horses). Development here, however, does not occur in a vacuum. Consider the normal developmental progressions for children in two different cultures that vary in their approach to science and math education. Chinese third graders seem to have no difficulty reasoning about inverse relations, whereas American third graders often do; American fifth graders achieve performance more like Chinese third graders (Zhou et al., 2000). Although further research is needed to confirm the reliability of this difference and to understand its sources, it may reflect differences in the quality of early mathematics and science education. In China, in contrast to the United States, the skills of argument and proof are taught as early as the first grade and mathematics and science topics are pursued more deeply and thoroughly. In addition, the elementary teachers are more highly trained in the teaching of mathematics.

Thus, although there is a clear age trend in learning to understand inverse relations, there can be dramatic differences in the age at which most children understand such relations as a function of educational and cultural

environment. The mechanisms behind such age differences are yet to be fully understood, but they make clear the folly of thinking that there are certain ages at which children can or cannot understand specific scientific concepts. And there is a continuing legacy of cognitive challenges in some areas. In more complex tasks, for example, college students have difficulties with inverse relations as well.

There are also developmental lags in how children understand trajectories, with an understanding in terms of catching actions appearing much earlier than those in terms of predictions as more passive observers (Krist, Fieberg, and Wilkening, 1993; Huber, Krist, and Wilkening, 2003; Krist, 2003). In fact, explicit predictions about trajectories are often wrong even in adults (Clement, 1982; McCloskey, 1983). Indeed, in some cases, very young children actually seem to be better at anticipating trajectories, then get worse as they get older and develop a more consistent but incorrect "theory" of motion (Kaiser, McCloskey, and Profitt, 1986). Such U-shaped developmental curves have been documented repeatedly in children's developing conceptions of mechanics (Karmiloff-Smith and Inhelder, 1974).

Children also show substantial improvement during the elementary school years in detailed understanding of physical mechanisms. Consider, for example, research on changes in children's understanding of gears. The mechanism is fully observable in these studies (a set of exposed gears), yet there is much that is not transparent to young children or even adults. One study that compared second and fifth graders showed how children can take an idea that is useful in one context and then overapply it to others (Lehrer and Schauble, 1998). Thus, a child might develop a hunch about gear function from playing with an egg beater and then inappropriately make some extensions to gears on a bicycle. More broadly, it can take years for elementary school children to start to understand systems like gears and levers in more formal terms that allow more correct generalizations across instances (Lehrer and Schauble, 1998). At the same time, children clearly benefit from core concepts that arise in infancy and the preschool years. For example, children of all ages insist that gears must make physical contact with each other in order to form a working system of gears.

Children have great difficulties learning physicists' notions of force. Students tend to associate forces with movement and do not recognize the action of forces in situations of equilibrium. They also tend to focus on forces as active agents and are less likely to recognize passive forces (e.g., they may think forces are needed more to start a motion than to stop one, hence have difficulty recognizing friction as a force). They also think of force as a property of objects rather than as a feature of interaction between two objects—so they identify forces singly, rather than in terms of interaction pairs. Finally, when two forces are acting on an object, they think of one as winning or overcoming the other, rather than interacting through

vector addition (Clement, 1982; diSessa, 1982). The developmental story seems to involve several distinct notions of force emerging at different times in childhood, with a final convergence on the physicists' concept usually occurring only in those lucky few who actually get insight from a college-level physics course instead of continuing to cling to developmentally earlier views (Ioannides and Vosniadou, 2002; Watts and Zylberstajn, 1981).

There are many other misconceptions that develop in childhood and often persist into adulthood without appropriate instruction. These include mistaken beliefs about relations between air pressure and gravity (Minstrell, 1982), confusions between momentum and force (diSessa, 1988), and difficulties in understanding magnetism (Barrow, 1987), among many others. As mentioned earlier, misconceptions should be seen as attempts by children to make sense of the world around them, often building on more correct notions that also coexist with the misconceptions (Clement, Brown, and Zietsman, 1989; Confrey, 1990). Misconceptions can often be understood as parts of a larger system of beliefs that do a good deal of cognitive work for the child. They also can reflect mistaken ontological commitments, which when changed allow the child to access other, more relevant, and already present concepts (Chi, 2005). Finally, they can be seen as necessary conceptual steppingstones on a path toward more accurate knowledge.

Extending and Revising Naïve Biology

During the elementary and early middle school years, children show major gains in their understanding of the living world. There is considerable growth in factual knowledge that starts to fill out conceptual frameworks. Children have opportunities to observe particular animals or plants (through caretaking or school activities) and learn more about what they do, what their parts are, what their insides are like, etc. Between preschool and fifth grade, children are able to list more and more internal body parts (Gellert, 1962). They also gain a better understanding of the function of those parts. Of course, that emerging understanding of anatomy and function is hardly complete by middle school. Most adults have huge gaps in their understanding of body structure and function in addition to misconceptions.

Children also learn about many more types of plants and animals. Whether through a visit to the zoo, reading a book about another country, or looking at animals and plants on line, there is a continual expansion in understanding about the diversity of kinds in the living world. There is also an increasing appreciation of the depth of biological taxonomies, with an emerging awareness of different subclasses of species, such as breeds of dogs.

In addition to the accumulation of facts, children in the elementary school years also appear to show restructuring of knowledge. They may reclassify some kinds of plants from nonliving to living (Hatano et al., 1997). Moreover, such shifts seem to be linked to cultural practices as well. For example, in a cross-national study of U.S., Japanese, and Israeli children, only 60 percent of Israeli fourth graders thought that plants were alive compared with over 90 percent of U.S. and Japanese children. Children may well shift to belief in the living nature of plants without explicit instruction or such cultural practices as gardening, but those forms of exposure may accelerate the process.

There is also growth in children's understanding of the human body as a machine (see Carey, 1985, 1995; and Cridier, 1981, for reviews). That is, with the development of an understanding of internal organs comes elaboration of ideas about how they function. Although these ideas may be quite simplistic, they represent an elaboration of their ideas about mechanisms, by combining some ideas of physical mechanism with body structure. Examples are coming to see the heart as a pump, coming to see the insides as consisting of interconnected tubes with vital nutrients transported to different parts of the body (e.g., Arnaudin and Mintez, 1985). Children also come to see that food is taken in, broken down into pieces, and then physically transported. They also gain some idea that human beings take in and breathe out air (exchange of materials). At the same time, they can miss many other mechanisms, such as that food is broken down not only physically but also chemically, or that there are many feedback loops operating between organs and systems.

Again, not only are elementary schoolchildren missing many details about the workings of plants and animals, but they also have a number of misconceptions. For example, as children come to recognize that plants are living things, they begin to overgeneralize that plants eat, sleep, etc. A powerful idea for them is that plants take in their food through their roots, rather than understanding that they synthesize sugars in their leaves from inanimate raw materials (Roth, 1984). There are many reasons why understanding photosynthesis is difficult, including limitations in their understanding of matter and atomic-molecular levels of description. Limitations in their conceptions of matter also affect their understanding of growth and decay.

These sorts of patterns also illustrate how domain knowledge interacts; limitations in one's understanding in one domain, that of matter, can constrain the kinds of ideas one can consider in another, that of metabolism. Again, many of these misconceptions persist in adults, who normally are quite surprised at how much of the mass of plants comes from the air around them.

One area of many misconceptions concerns cellular levels of functioning and mechanisms (Dreyfus and Jungworth, 1989; Flores, Tovar, and Gallegos, 2003). Of course, many of these problems are failures to develop any meaningful level of description or explanation at a cellular level. Students may think of cells as inanimate or confuse atoms and cells. Further-

more, without an atomic-molecular level of description, it is hard to understand what cells are doing (to understand cellular metabolism, etc.). They may have an anthropomorphic view of cells as making decisions and see the nucleus as directing all cell processes. They may also see cells as engaging in miniature versions of macroscopic processes. For example, they think of nutritive processes in cells as analogous to macroscopic digestive processes where food is ground and processed; or they confuse cellular respiration with macroscopic processes of breathing (Flores, Tovar, and Gallegos, 2003). Thus, they lack distinct descriptions of processes at the atomic-molecular and cellular levels that would provide deeper, mechanistic explanations for macroscopic phenomena. Overall, they seem to retain a simple macroscopic conception of the workings of the human body—and a very limited one at that.

At a more systemic level, children's understanding of the origin of living things undergoes considerable change. Between about 8 and 10 years of age, children develop a more explicit creationist explanation of the origins of species, regardless of beliefs in their homes (Evans, 2001). Such beliefs may reflect the formation of an explicit theory based on their initial essentialist bias—that is, their initial tendency to believe that things have a true underlying nature. Thus, a belief that species have fixed essences works against the necessary concept of a species as a probabilistic distribution of traits on which natural selection operates. That essentialist bias, however, is not merely a problem confronted by children. Indeed, it has been argued that the relatively late emergence of evolutionary theory in the history of science was because of the essentialist biases in most adult theories of species (Hull, 1965; Mayer, 1982), leading one scholar to remark that essentialism had resulted in a "2000 year stasis" in evolutionary thought.

This continuing difficulty with evolutionary thought in adulthood is also borne out in work showing that college-educated adults also frequently answer questions about evolution and natural selection in ways that are not in accord with evolutionary theory (Shtulman, 2006). Thus, essentialist biases can distort judgments about a wide range of evolutionary phenomena, including variation, inheritance, adaptation, domestication, speciation, and extinction (Shtulman, 2006). It may also be the case that evolutionary thought is hampered in childhood and beyond by another bias that emerges in the first year of life, that of seeing intentional agents as the only plausible causes of ordered relationships in the world (Newman et al., 2006). When tested as to whether an inanimate entity, such as the wind, or an animate one, such as a person, could cause a disordered array to become ordered, 1-year-olds and preschoolers strongly prefer the animate agent, while showing no preference when the situation is reversed, that is, the cause of an ordered array becoming disordered. This bias may be related to the argument from design, a centuries-old belief that the elaborate functional structure of the living world must be caused by intentional agents who "designed" those living things.

The study of children's intuitive biology has also revealed strong cross-cultural variations that seem to be closely related to cultural practices and traditions. Thus, children in non-Western traditional cultures often seem to have more sophisticated notions about taxonomies, ecology, and what properties are likely to be shared among various groups of animals and plants (Atran et al., 2001; Atran, Medin, and Ross, 2004; Ross et al., 2003; Waxman and Medin, in press). The simple act of raising a goldfish can help a child move to more sophisticated forms of biological thought (Inagaki and Hatano, 2001). One intriguing interpretation of cultural differences has emerged from a comparison between cross-cultural studies and changes in beliefs about biology through the course of history. It appears that with respect to an understanding of the taxonomies of genera, species, and subspecies, there has been a gradual devolution of biological knowledge in Western urbanized cultures over the past 400 years (Wolff, Medin, and Pankratz, 1999; Atran, Medin, and Ross, 2004).

Expanding Understandings of Matter and Its Transformation

We discussed how preschool conceptions of matter and its transformation continue to change in the elementary school years. In addition, we treat this topic in depth in Chapter 8 where we discuss how a learning progression can be developed for teaching about matter and the atomic-molecular theory. We therefore provide only a brief overview here to illustrate the complexity of the terrain children will have to cover, some of the shifts in conceptualization that can occur along the way, and how different ideas interact with each other and with forms of teaching.

There is now an extensive literature of misconceptions in the area broadly known as chemistry. Misconceptions have been documented in concepts of burning (Boujaoude, 1991), the nature of gases (Benson, Wittrock, and Baur, 1993), the particulate nature of matter (De Vos and Verdonk, 1996), and many other areas (Abraham et al., 1992; Andersson, 1990). One major area of difficulty involves coming to conceptualize gases as material bodies. Students tend to think of gases as immaterial and ethereal—belonging to an ontologically different category than solids and liquids.

Another major difficulty involves developing a macroscopic conception of chemical substances (as characterized by its properties such as boiling and melting points, different spectra, etc.) that allows them to identify substances and track the ways substances can go in and out of existence in chemical change (Johnson, 2000, 2002). Although very young children tend to identify material kinds by their perceptual properties, during elementary

school children increasingly trace the identity of materials through their transformational history (e.g., sawdust comes from grinding up wood, so it must still be the same kind of stuff with some of its properties). This move can lead them to "hyperconservation of material kind"—a commitment to thinking that the identity of material is generally preserved which prevents them from being able to engage with the idea of chemical change. For example, they may see chemical changes as involving simply the mixture of substances whose identities are maintained during the process. Yet attending to transformation history can spawn productive insights in other contexts. For example, it allows them to think of materials as underlying constituents that maintain some core properties and to explain the properties of large-scale objects in terms of the materials of which they are composed. This move may be quite helpful to them in constructing an initial understanding of density as an intensive characteristic of materials.

Ultimately, however, in developing an understanding of atomic-molecular theory, students will need to reconsider the relation between properties that characterize entities at macro and micro levels and the ways assumptions about entities at the micro level can be used to explain observable phenomena. For example, although some macro-level properties are explained in decompositional terms (e.g., the weight and mass of an object is a function of the weight and mass of the atoms or molecules of which it is composed), other macro-level properties are emergent characteristics explained in terms of interactions among entities at the micro level. For example, objects are solid not because they have solid atoms, but because of bonding patterns among atoms and molecules. Thus, another major area of difficulty concerns linking up micro-level processes and entities with macro-level phenomena (Ben-Zvi, Silberstein, and Mamlok, 1989). Thus, elementary schoolchildren often have difficulty seeing how micro-level entities are related to macro-level ones, sometimes thinking that everything must appear the same at all levels of analysis (Nakhleh and Samarapungavan, 1999).

Unfortunately, an understanding of the distinction and linkages between macro and micro levels is often obscured by current teaching approaches that do not engage students with thinking through these issues and that have not systematically developed students' epistemological understanding of the nature of models and theories. Students may be introduced to atoms and molecules through thought experiments about dividing materials into little pieces. This approach encourages students to think of atoms and molecules as just little pieces of materials that inherit all of their macroscopic properties. They then may not recognize that atoms/molecules are preexisting entities with distinct properties and characteristics (Pfundt, 1981). Students may be taught about the atomic-molecular theory as a "rhetoric of conclusions" or list of facts, rather than being engaged in model-based reasoning and exploring how to explain and make sense of a wide range of phenomena (Lee et al., 1993; Snir, Smith, and Raz, 2003). In addition, they often are presented with such an impoverished view of the atomic-molecular theory (e.g., no discussion of atoms and molecules as discrete particles separated by empty space or of the role of bonds in holding particles together) that students cannot possibly understand how to explain macroscopic phenomena in atomic-molecular terms (Nussbaum, 1998).

Fortunately, innovative approaches to teaching students about atoms and molecules indicate that middle school students can engage with these issues and benefit greatly from teaching approaches that encourage them to think through these issues (Lee et al., 1993; Meheut and Chomat, 1990; Nussbaum, 1998; Snir, Smith, and Raz, 2003; see Chapter 8 for a discussion of some of these innovative teaching approaches.) Further, there is evidence that being able to think about matter in atomic-molecular terms feeds back and helps clarify children's understanding of the material nature of gases, phase change, chemical substance and chemical reactions (Lee et al, 1993; Johnson, 1998, 2002).

In short, it takes many years to work out the subtleties of the appropriate constituents of matter and how they combine to create larger units all the way up to those that are macroscopically observable. As children try to figure out these relations, they do make a large number of mistaken inferences about the nature of matter and its transformation. Above and beyond those mistakes, however, are some more accurate beliefs about the different kinds of matter, some sense of conservation, and what sorts of properties are likely to be the most useful in identifying substances.

An Expanding Theory of Psychology

We have explained that infants and preschoolers are acutely sensitive to intentional agents and that they make a wide range of causal attributions about intentional agents that they do not make for other kinds of agents. By the end of the preschool period, they have learned how to think about the relations between true and false beliefs and actions in contexts related to those beliefs. These insights, however, are only the beginning of a long process of increasingly subtle insights into the workings of the minds of others, insights that continue well into adolescence. For example, only in the middle of elementary school do children start to clearly understand that an individual can simultaneously have two conflicting desires or beliefs (Choe, Keil, and Bloom, 2005). Similarly, it can take many years to understand that different people might see ambiguous events quite differently because of the different expectations or biases they bring to the situation (Barquero, Robinson, and Thomas, 2003; Mills and Keil, 2005; Pillow and Henrichon, 1996). The more subtle consequences of thought, such as that cognitive inferences can be sources of knowledge, also take time to develop (Pillow

et al., 2000). As we discuss in Chapter 5, views toward knowledge as constructed and subjective tend to emerge in middle childhood. These increasingly sophisticated views toward knowledge are related to a child's developing understanding of the ways in which knowledge is gained in the sciences as well.

There are, however, signs of a continuing influence of theory of mind errors in children and adults. For example, Keysar, Lin, and Barr (2003) asked adults to play a communication game where one person played the role of a director who directed another person (the participant) to move objects around on a grid. Before receiving instructions, the participant hid an object in a bag such that the director did not know its identity. During the game, the director sometimes described an object in the grid that both people could see in ways that more closely matched the object hidden in the bag. Although the participant knew the director was unaware of the identity of the object in the bag, he or she often thought the director was referring to the hidden object, sometimes even attempting to follow the director's instruction by moving the object in the bag instead of the object on the grid. These kinds of mistakes are predicted from vestiges of failures that young children make about false beliefs (Keysar, Lin, and Barr, 2003). Similarly, egocentrism, a difficulty in taking the points of views of others, can have strong influences on adult inferences into the mental states of others. More subtle misconceptions concerning the nature of perception also persist into adulthood. For example, many adults believe that, in order to see, something must leave the eyes (extramissionist view). That is, the perceiver "projects" rays out of the eyes into the world that "see" objects. This belief often influences adult judgments of how other humans perceive (Cottrell and Winer, 1994).

Toward a Mature Cosmology

As mentioned earlier, much of the work on the child's emerging understanding of cosmology spans the preschool and elementary school years, making a discussion here of later developments less necessary. It is worth briefly noting, however, that a great deal of detailed knowledge about cosmology can be acquired during the elementary school and middle school years, although progress here is typically quite variable. Many children learn more and more about astronomical bodies and their distinctions, such as stars and planets. Some even start to understand more clearly the Copernican view of the solar system, although research has shown that misconceptions about the explanation of day and night and the seasons can extend into the adult years. Furthermore, it can take many more years to correctly understand the basis for the tides, eclipses, and the nature of distances in the universe.

A review of three decades of research on learning about Earth's spherical shape and gravity (Agan and Sneider, 2004) found that until fourth grade it is very difficult for students to fully grasp the spherical Earth concept, with gravity pulling objects toward Earth's center, and that "achieving conceptual change at such a deep level requires clarification of current ideas (even if those ideas may be wrong), listening to the ideas of others, thinking through the logical implications of different models, and then applying conceptual models to explain previously observed phenomena." Yet, taking the time to construct such a robust Earth concept may be worth it for several reasons. First, it provides a foundational framework for constructing explanations of many important phenomena that connect to children's daily lives such as the reasons for day and night and the causes of the seasons. Second, it provides a wonderful opportunity for engaging in model-based reasoning during the elementary school years and developing important epistemological understandings of models.

Critical to an account of cosmology is a recognition that most adults through most of history have held views that are radically different from those held by scientists today. Errors and mistakes are, in that sense, the norm for individuals of all ages and not merely during a period of development.

Summary of Knowledge Growth Across the Domains

A few themes cut across all domains in discussions of knowledge growth after preschool. First, it is clear that older children are building on the products of preschool knowledge growth. The cognitive achievements of infants and toddlers provide older children with foundations for further understandings in each domain. It is easy to see how notions of mechanics, folk psychology and folk biology, for example, persist into later childhood and influence the ways in which more detailed mental models are constructed.

Second, a great deal of development during the elementary school years involves learning about more detailed mechanisms and facts in various domains. The surprisingly abstract frameworks and expectations that develop in the early years are now supplemented by more concrete ways of fleshing them out. Whether it is specific notions of digestion, blood flow, burning, or gear action, children attempt to work out the concrete details in each domain in ways that honor the legacies of preschool and infancy.

Third, children's attempts to develop more concrete models result in a large number of misconceptions. Concreteness can lead to commitments that create mistakes. Children's misconceptions can be dramatic, but they do not really represent a step backward from earlier ages when those misconceptions might be weaker or not even present. In many cases, moving through a series of misconceptions may be the only plausible way for a child to

progress toward a more correct and detailed notion of mechanism. In addition, many misconceptions persevere into adulthood, illustrating that misconceptions will always be a by-product of attempts to build more precise accounts of how the world works.

Finally, the elementary school years and beyond can include impressive periods of conceptual change. Children will come to reassign entities to different ontological categories, they will put together concepts to create new ones, and they seem to have dramatic new insights that can change the way they understand a whole domain. It is equally clear that there is a real diversity in the kinds of conceptual change that occur, a diversity that must be understood to have a full account of how the foundations of a scientific knowledge emerge in childhood. That topic is the focus of the next section.

THE NATURE OF CONCEPTUAL CHANGE

As described in the preceding chapter, one of the surprising discoveries of the past few decades of research in developmental psychology is the tendency for children to search for mechanisms and the important ways ideas about mechanisms inform their reasoning and inference in everyday life. As we've said, children are by no means the blank slates or concrete, atheoretical reasoners that previous theorists have claimed. Instead, they have some existing concepts, constrained by either framework theories (Inagaki and Hatano, 2002; Vosniadou and Ioannides, 1998; Wellman and Gelman, 1992), modes of construal (phenomena in a domain are assumed to correspond to certain causal patterns; Keil, 2003), or skeletal principles (innate, abstract guidelines; Gelman and Lucariello, 2002), that help them carve the world up into different domains and organize their expectations about how different types of things should behave. These concepts help them organize and make sense of the world, support categorization, inductive and deductive inference, problem solving, explanation, as well as language learning and comprehension (Carey, 1999; Thagard, 1992; Wellman, 1990).

The research of the past few decades has thus revealed greater similarities between the concepts of children and those of scientists, avoiding simplistic dichotomies in which the concepts of the two are seen to be fundamentally different types. Not only is there now greater recognition of the implicit explanatory and systematic constraints on children's concepts (Carey, 1999; Gelman and Lucariello, 2002; Keil and Lockhart, 1999; Wellman and Gelman, 1992) but also of the implicit, informal aspects of scientific concepts (see the pioneering work of Clement, 1991, 1993, and Nersessian, 1992, in this regard). In addition, philosophers and historians of science have long recognized the role of guiding paradigms and frameworks, in which many deeply entrenched assumptions are not consciously emphasized or subjected to investigation, just assumed (e.g., Kuhn, 1970; Lakatos, 1978).

Greater awareness of the similarities between children's and scientists' concepts also allows one to consider the differences between them. Some researchers suggest that children's concepts may differ from those of scientists because they are embedded in different theories or constrained by somewhat different assumptions about the origins of the natural world and the nature of knowledge. Clearly, the current theories of science are immense intellectual achievements that are the products of centuries of investigation and testing carried out by entire communities of adult experts. Furthermore, the history of scientific ideas documents the profound changes in proposed theories and explanatory ideas that have occurred as scientists have struggled to develop, test, and refine their theories. Many of the concepts in these theories are counterintuitive, far removed from the first guesses one would have made about what the world is like and how it functions. In this view, learning science is difficult not because of what children don't have or lack, but because of what they do have: some initial commitments and ideas that will need to be revised and changed.

Forms of Conceptual Change

Conceptual change can take a variety of forms that can vary in degree and difficulty (Carey, 1991; Chi, 1992; Keil, 1999; Thagard, 1992). A challenge for conceptual change researchers is to provide a typology of important forms of conceptual change that occur, especially in the course of science learning. Most researchers make a distinction between changes that are relatively easy, because they are basically consistent with students' initial conceptual structure, and ones that are more difficult because they call for more fundamental revisions to that structure. In the latter group, some make further distinctions based on the extent of the restructuring involved and the degree that such restructuring violates students' most central ontological commitments.

Science education presents many opportunities for multiple kinds of change that vary in difficulty. Teachers and curriculum developers are often not aware of these different levels of difficulty and hence don't appropriately modify their methods of teaching when confronting different types of cases.

Elaborating on an Existing Conceptual Structure

At one level, students are relatively quick to learn new concepts that fit within an existing conceptual structure, such as new subkinds or superordinates or new parts or properties of particular kinds. For example,

learning about new kinds of animals (e.g., aardvarks, emus) or subkinds of dogs (e.g., German shepherds, bulldogs) need not require a change in the child's concept of animals or dogs. The child already knows that animals (or dogs) can vary in size, body type, eating preferences, and temperament. Thus, identifying new kinds that have different clusters of these attributes enriches the child's understanding of the diversity of animals or dogs without fundamentally challenging the organizing principle on which their concept of animal or dog is based. Similarly, adding a new superordinate that unites subkinds (e.g.. learning that bears, dogs, and cats are all mammals) need not be difficult, especially when there are some easy-to-understand common properties that unite these kinds (e.g., they are all warm-blooded and nurse their young) and when the new kind called "mammals" can be understood as a special kind of animal.

Restructuring a Network of Concepts

In other cases, children need to restructure their understandings of an entire network of concepts that are used to understand or explain phenomena in a given domain. In these cases, there are multiple coordinated changes in the conceptual groupings used, and not a simple one-to-one correspondence between the concepts of the earlier and the later network.

In conceptual differentiation, the newer (descendant) theory uses two distinct concepts whereas the initial (parent) theory used only one, and the undifferentiated parent concept unites elements that will subsequently be kept distinct and regarded as fundamentally different kinds. For example, children initially conflate dead/not real/inanimate in an undifferentiated concept of "not alive," which subsequently is rearticulated as separate concepts characterizing fundamentally different kinds of things (Carey, 1985, 1999). In another case, children initially conflate heavy/heavy-for-size in an undifferentiated concept of "felt weight," which is subsequently reanalyzed as weight (an extensive physical quantity) and density (an intensive quantity) (Carey, 1991; Smith, Carey, and Wiser, 1985). Conceptual differentiation is different from simply adding two new subcategories to an existing category (as when one learns to distinguish two different types of dogs), because in those cases the parent concept "dogs" remains intact when the subtypes are added. In differentiation, the parent concept is seen as incoherent from the perspective of the subsequent theory and plays no role in it.

Conceptual differentiations are typically accompanied by conceptual coalescences, another fundamental form of conceptual change. In coalescences, the descendant theory introduces a new concept that unites concepts previously seen to be of fundamentally different types in the parent theory. For example, children initially see solids and liquids as fundamentally different from air (Smith et al., 1997; Stavy, 1991). Later they may come to see them all as distinct forms of matter. For another example, children initially see rest as the opposite of motion. Later, in learning physics, they come to see both rest and uniform motion as "unaccelerated" states resulting from balanced forces. Conceptual coalescence is different from simply adding a more general category by abstracting properties common to more specific categories. In coalescence, the initial concepts are thought to be fundamentally different kinds, and the properties or relations that will be central to defining the new superordinate category are not explicitly represented or considered central to the initial concepts.

Two additional forms of conceptual change frequently accompany conceptual differentiations and coalescences and can contribute to the restructuring: (1) there can be changes in what characteristics are seen as central or peripheral to (multiple) concepts and (2) something that was originally conceptualized as a property may be reconceptualized as a relation (or vice versa). For example, in coming to form a biological concept of living things that includes both plants and animals, children may shift from the view that being active and moving without outside intervention are more central to living things, to the view that having a life cycle (involving reproduction, growth, and death) and engaging in basic processes to sustain life (such as getting food, water, air) are more central. These changes in turn require coordinated changes in children's related conceptions of reproduction, growth, death, eating, drinking, and breathing as well, as they develop a more abstract sense of how these processes can apply to organisms as different as plants and animals.

Similarly, in order to rationalize the inclusion of air, solids, and liquids into a single category of matter, children must move from thinking of matter as something perceptually accessible (as something one can see, feel, touch) to thinking of it as something that takes up space and has weight. This change in turn requires changes in their initial concepts of taking up space and weight—for example, reconceptualizing weight from something that is primarily perceptually defined and assessed (i.e., weight as felt weight) to an objective magnitude that is measured and quantified. This reconceptualization also supports making a principled differentiation between weight and density.

Adding New (Deeper) Levels of Explanation

Learning science with understanding requires that children reconceptualize their initial concepts to describe macroscopically accessible objects and events. It also requires that they add new levels of conceptual description (e.g., descriptions of the behavior and interactions among atoms and molecules, of the structure and functioning of individual cells), in order to provide deeper layers of explanation. Adding these new levels is difficult for

several reasons. First, these levels may build on some of the previous restructurings described above and provide deeper explanation of many phenomena. Given that many students do not achieve those understandings, they do not have an appropriate foundation for constructing the next level of explanation.

Second, these new levels can interact and mutually support each other. For example, a deep understanding of cell theory and basic biological processes of living things actually calls for students to integrate atomic-molecular ideas into their analyses of living things. Without that foundation and level of analysis, many of the ideas of cell theory remain hard to explain or understand. Finally, adding these new levels calls for greater sophistication than many students have. For example, it requires that students understand the nature and purpose of explanatory models and how they are evaluated. That is, they are evaluated on the basis of their ability to explain a pattern of evidence rather than on whether they "look like" what is to be explained. If students do not have this kind of understanding, they may reject claims about atoms—such as that they are in constant motion—because these violate their commonsense impressions.

Mechanisms of Conceptual Change

One reason for distinguishing more fundamental, "revolutionary" conceptual changes from belief revision or conceptual elaboration is that these more profound forms of change may require a more complex coordination of a variety of learning mechanisms than more typical learning does. Most everyday learning involves knowledge enrichment and rests on an assumed set of concepts. For example, people use existing concepts to represent new facts, formulate new beliefs, make inductive or deductive inferences, and solve problems. Fundamental conceptual change, in contrast, involves coordinated adjustments of a variety of sorts in students' network of concepts. The concepts of the new theory are ultimately organized and stated in terms of each other, rather than the concepts of the old theory, and there is no simple one-to-one correspondence between some concepts of the old and new theories. By what learning mechanisms, then, can students comprehend a genuinely new set of concepts and interrelations and come to prefer them to their initial set of concepts?

Acquiring New Knowledge Over an Existing Base of Concepts

First, the acquisition of new knowledge about the world (building on an initial base of concepts) is certainly an important part of the process of conceptual change (Carey, 1985; Chi, 1992; Case, 1997). For example, young children certainly won't change their understanding of living things without learning about internal body organs and their function; they won't deepen their understanding of materials without learning about a variety of materials and their characteristics. The claim being advanced by conceptual change researchers, however, is that, although such new knowledge may be necessary for conceptual change, it is not sufficient to produce it (Carey, 1991; Inagaki and Hatano, 2002).

Some of the strongest evidence for this claim comes from the repeated failures of both traditional science instruction and simple discovery learning to produce understanding of scientific ideas for large numbers of students. Such failures have been found in domain after domain, such as photosynthesis (Roth, 1984), atomic-molecular theories of matter (Lee et al., 1993), and weight and density (Smith et al., 1997). Traditional instruction exploits simple knowledge-telling strategies of teaching and conveys science as a rather flat "rhetoric of conclusions" (Schwab, 1962). Simple discovery approaches have students do experiments or make observations with the naïve hope that the scientists' conclusion will emerge unproblematically from the data (Roth, 1990, 2002). Given that both these didactic and discovery teaching approaches are certainly introducing students to a wealth of new knowledge and experiences, these findings underscore that being exposed to new information is not the same as remembering or understanding it. Indeed, in one study of a special cognitively impaired population with Williams Syndrome (Johnson and Carey, 1998), it appeared that simple knowledge accumulation was possible for this group in the area of biology but not the more revolutionary cases of conceptual change, which may require much deeper causal explanatory understandings to occur.

Metacognitively Guided Learning

Children's metacognitive abilities may be critical to many cases of fundamental conceptual change (Beeth, 1998; Case, 1997; Inagaki and Hatano, 2002). Metacognition or "thought about thought" refers to a broad range of processes, including monitoring, detecting incongruities or anomalies, self-correcting, planning and selecting goals, and even reflecting on the structure of one's knowledge and thinking (Gelman and Lucariello, 1992). Even preschool children have some metacognitive abilities, but major expansions in these abilities during the elementary school years may create especially powerful support for more dramatic forms of conceptual change.

Metacognitive abilities may foster conceptual change by detecting and monitoring incongruities in an existing conceptual system. This alerts the learner to potential problems, but it does not itself reveal the nature of the problem or its resolution (Gelman and Lucariello, 2002; Inagaki and Hatano, 2002). When an unexpected result arises, there can be many reasons for the anomalous data: a fluke result, poor data collection technique, a faulty

hypothesis, a limited framework theory, among others (Chinn and Brewer, 1993). More explicit metacognitive knowledge (that allows one to identify and describe different sources of problems) can help direct the learner's attention to determine the likely source of the problem given further information. For example, the learner might check to see if the result is reproducible, reexamine the data collection methods, compare results with other groups, etc. Thus, a second function of metacognition is a more directive and reflective one: to consider possible reasons for the incongruity and gathering or selecting further information that helps refine one's understanding of the problem. Adding a reflective component to learning not only speeds up the time it takes to learn, but also makes it possible to learn things that one might never figure out through trial and error (Case, 1997).

Evidence that metacognition plays a key role in conceptual change learning comes from a variety of types of studies. The instructional techniques that have been shown to be effective in producing conceptual understanding of new science content all have a strong metacognitive component (Minstrell, 1982, 1984; Nussbaum and Novick, 1982; Chinn and Brewer, 1993; Roth, 1984; Brown and Campione, 1994; Hennessey, 2003; Beeth and Hewson, 1999; National Research Council, 2000). Typically, activities are introduced to make students aware of their initial ideas and that there may be a *conceptual problem* that needs to be solved. Students may be asked to make a prediction about an event and give reasons for their prediction, a technique that activates their initial ideas and makes students aware of them. Class discussion of the range of student predictions foregrounds alternative ways of thinking about the event, further highlighting the conceptual level of analysis and creating a need to resolve the discrepancy. Gathering data that expose students to unexpected discrepant events or posing challenging problems that they cannot immediately solve are other ways of sending signals to students that they need to stop and think, step outside the normal "apply" conceptual framework mode, to a more metaconceptual "question, generate and examine alternatives, and evaluate" mode. In addition, experimental manipulation of the amount of reflective inquiry and self-assessment in two identical versions of a carefully designed inquiry unit on motion for sixth graders produced greater gain scores for the students in the classroom with enhanced opportunities for reflective self-assessment (White and Frederickson, 1998). Particularly important, the gains were evident for all ability levels; indeed, they were highest for students with lower ability levels.

Elementary schoolchildren have much more capacity for metacognitively guided learning than has been commonly supposed or taken advantage of by existing science curricula (see Hennessey, 2003, for a detailed analysis of the subtle and diverse expressions of metacognitive understandings shown by her students in science class in grades 1 through 6). These abilities are typically overlooked and untapped in traditional approaches to science teaching, and, as a result, they not only fail to develop those abilities further, but also reduce the chances of conceptual change.

Constructing New Conceptual Representations

Conceptual change often requires an ability to imagine and understand alternative ways of conceptualizing the problems under consideration (Strike and Posner, 1985; Inagaki and Hatano, 2002; Carey, 1999). Indeed, research has shown that students are reluctant to abandon an initial idea, however imperfect, if there is not a better idea available (Karmiloff-Smith and Inhelder, 1974; Chinn and Brewer, 1993). Instead they are likely to ignore or discount the challenging data, consider that their idea works most but not all of the time, or make local patches. For this reason, researchers have noted the limitations of "discrepant events" as catalysts of conceptual change. Although they can be helpful in arousing interest, they may be counterproductive if introduced too soon before students have the conceptual resources to resolve them. Furthermore, they are not the only means of motivating conceptual change.

How can students construct a new set of conceptual representations? They need to draw on existing resources in their conceptual system—things they already understand in some context or that make sense to them. Drawing on and connecting to these resources is essential if the new conception is going to be intelligible to them—something often overlooked when they are presented with explicit formal definitions that they cannot understand. Some of these resources may come from *within* their initial theory for a given domain (e.g., as they learn about new internal body parts or organs of human beings, or elaborate on their understanding of eating, growing, and breathing). Others may come from understandings students have *outside* the domain (e.g., as they draw on their knowledge of number in constructing measures of physical quantities, such as weight).

Students then need to use a variety of heuristic procedures and symbolic tools to exploit these resources in constructing new representations of the problem. For example, heuristic procedures, such as analogical and imagistic reasoning, thought experiments involving extreme and limiting case analyses, and inference to best explanation allow students to creatively extend, combine, and modify existing conceptual resources through the construction of new models (Nersessian, 1989, 1992; Clement, 1991; Gentner et al., 1997; Kuhn, 1977; Carey, 1999). Symbolic tools, such as spoken and written language, diagrams, pictures, and algebraic, geometric, and graphical representations of mathematics, and other invented or culturally transmitted notational systems, allow the explicit representation of key relations

in the new system of concepts (Gelman and Lucariello, 2002, discuss this as forming rerepresentations) (see also Lehrer et al., 2000).

Even preschool children can use many of these heuristic techniques in limited contexts and in domains they understand, although they certainly do not yet coordinate them in the service of serious model-based reasoning. For example, even 3-year-olds can engage in analogical reasoning (Goswami and Brown, 1990); they can also engage in inference to best explanation, as when they infer a hidden causal mechanism to explain an observable event (Bullock and Gelman, 1979). Thus, conceptual change researchers are finding that involving elementary, middle, and high school students in discovery argumentation via cycles of model-based reasoning—practices very similar to those used by scientists themselves—are highly effective means of building these new understandings (Brown and Clement, 1989; Lehrer et al., 2001; Smith et al., 1997; Stewart, Cartier, and Passmore, 2005; White, 1993; Wiser and Amin, 2001). Such modes of teaching and presentation are dramatically different, however, from those employed in traditional instruction (see Box 4-1).

BOX 4-1 An Example of Discovery Argumentation

An example of a powerful form of discovery argumentation is the "bridging analogies" strategy (Brown and Clement, 1989; Clement, 1993). In this strategy, one identifies a *target situation* in which students' initial intuitions are at variance with the expert analysis. For example, students do not see a book resting on a table as involving balanced forces (i.e., the force of the book on the table is equal and opposite to the force of the table on the book). Instead, they think that only the book is pressing on the table, or that it is pressing down more than the table is pressing up (hence, the book stays down). In fact, they often don't think of a table as the sort of thing that *can* exert a force; it is conceptualized as a passive resistance or support.

Then one looks for an *anchoring intuition*—a situation in which the students' intuition is in line with the expert analysis, even though they may not yet share the same general conception of force with the expert. For example, students see a book resting on an outstretched hand as a clear case of balanced forces, because the student can actively feel and imagine exerting greater and greater force as more books are piled on to actively compensate for the weight of the book.

Students initially see these two situations as entirely different from each other. Then one presents a series of bridging analogies—new situations that are intermediate between the target and the anchor, such as a metal coiled spring. The metal coil shows visible compression when the book is placed on it, which helps the student see the situation as like the hand, with which the student can feel the push and counterpush. Yet unlike the hand, it is an inanimate object. Students can engage in cycles of reasoning about these situations and in the process construct a new model of the situation, in which they can imagine the molecules in the table undergoing compression when the book is placed on it and pushing back with equal and opposite force. They can they test their prediction by checking if, in fact, there is a (slight) compression of the table when the book is placed on it.

Clement and his colleagues have exploited this bridging analogies strategy, in combination with other techniques, throughout a high school physics curriculum (Camp and Clement, 1994). In addition, they have directly compared the effectiveness of this mode of discovery argumentation with more traditional modes of argumentation in making new ideas intelligible and plausible to students (Brown and Clement, 1989). Both approaches use a variety of everyday examples as well as present an important "big idea," but the examples are organized and presented entirely differently in relation to the big idea.

In the traditional approach, the big idea is stated as a general principle, such as Newton's third law. It is assumed that the general principle is immediately intelligible to students, and that each of the subsequent examples will be compelling and readily interpretable in terms of the general principle. There is no consideration that students may have alternative ideas that are inconsistent with both understanding and accepting this general principle.

In the bridging approach, it is assumed that students have an alternative way of thinking about the target situation, but that they have resources available (in the form of physical intuitions about different physical situations) that can be drawn on in constructing a new representation of the target situation. In addition, students are led to formulate the big idea through a chain of reasoning about specific situations. Finally, the big idea takes the form, not only of an abstract general principle, but also of a model of the situation that incorporates both abstract elements and physical intuitions, which allows them to see the situations in new ways. The results of their study were striking: students were able to understand Newton's third law more thoroughly and apply it to novel situations when presented with text that used the bridging analogy argumentation (Brown and Clement, 1989).

The recent interest in having science instruction focus on helping students to construct and evaluate abstract models of situations fits with the recognition that effective science learning calls for students to construct new representations that differ in important ways from those used in everyday life. Science involves more than gathering new data and making inductive generalizations from those data; it also involves new ways of seeing those data in terms of idealized representations. Although there are many approaches to building these models in different domains, science commonly incorporates mathematical relations in these models (Nersessian, 1992) as well as physical intuitions and sensorimotor schemas (Brown, 1993; Clement, 1991). As Nersessian (1989) points out, "in learning Newtonian mechanics, students must usually also learn how to construct an abstract, mathematical representation of the physical world for the first time." Thus, science educators should not neglect teaching students some of the idealization techniques (such as thought experiments and limiting case analyses) that are central to constructing those abstract representations and that can facilitate their recognition of deep analogies between superficially different phenomena.

Strengthening New Systems of Ideas

Constructing a new system of ideas does not, of course, ensure that these ideas will be internalized (i.e., frequently used in appropriate contexts or that they will even be preferred to one's initial ways of thinking). How does a new conceptual system become strengthened and gain ascendancy over one's initial ideas? Many conceptual change researchers have considered that engaging in argument may be a central part of this process (e.g., Chinn and Brewer, 1993; Strike and Posner, 1985; Thagard, 1992). More specifically, students are asked to evaluate (or debate) the adequacy of the new system with known competitors. For example, the new system will gain ascendancy if seen as more plausible (consistent with prior knowledge and existing data) and fruitful (generative of further questions) (Strike and Posner, 1985). Or the new system will be favored if it is seen as more explanatorily coherent (Thagard, 1992); a variety of aspects contribute to judgments of coherence, such as explanatory breadth, elegance, simplicity (not ad hoc), avoidance of contradiction, and future prospects. Even elementary school students are sensitive to many of these features in judging rival accounts. More specifically, Samarapungavan (1992) found that children prefer accounts that explain more, are not ad hoc, are internally consistent, and fit the empirical data. An important step in evaluating an argument may first be to discuss and construct some shared norms for argumentation not only among students but also with the broader scientific community they are trying to understand (Brown and Campione, 1994; Beeth, 1998; Beeth and Hewson, 1999; Duschl and Osborne, 2002; Sandoval, Reiser, 2004).

Argumentation and repeated application of new ideas are both important and may involve complementary, but also mutually supportive, processes. Argumentation is a more explicit "meta-process," whereas repeated practice in application involves (in part) gaining lower level associative strength. At the same time, argumentation from patterns of evidence involves practice in application, and repeated application can also provide additional opportunities for metacognitive reflection. Indeed, many science educators believe that a key to promoting conceptual change in the classroom is to create a more reflective classroom discourse that is structured around explicit argumentation (Hennessey, 2003; Herrenkohl and Guerra, 1998; van Zee and Minstrell, 1997). In addition, longitudinal studies of conceptual change highlight the importance of elaboration and depth of coverage (Clark and Linn, 2003), opportunities to revisit key ideas introduced in benchmark lessons (diSessa and Minstrell, 1998; Minstrell, 1984; Minstrell and Kraus, 2005; Roth, Peasley, and Hazelwood, 1992), and continued use of key ideas in subsequent courses in which they are further elaborated (Arzi, 1988).

Developmental Change That Is Not Conceptual Change

It is important to note that not all developmental change in performance on science-related tasks involves conceptual change. Some kinds of change can often appear superficially to be conceptual change but in fact may be quite different. Consider cases of increasing access to conceptual systems and increasing relevance. Increasing access can be illustrated by an analogy of a child learning to use a heavy hammer. The child may only be capable of using the hammer to hit nails at eye height or lower, as the hammer is too heavy to use for higher level objects. As her arm gets stronger, she can use the hammer in new tasks. Her basic skills at hammering may not have changed in important ways, only her general arm strength. Similarly, a child may have a conceptual system that she uses to understand a phenomenon, but because of more general memory or attentional limits, she may not be able to use it in as wide a range of tasks as an older child. Change here may not involve new conceptual insight, but merely increasing processing capacity, memory storage, or attentional ability. A child who fails to engage in transitive reasoning with a set of inequalities may be failing not because he doesn't have the concept of transitive relations, but rather because he cannot remember as many relations as an older child. When that memory is assisted, he can see the transitive relations as well (Bryant and Trabasso, 1971). Thus, some tasks may, for cognitive reasons not related to conceptual change, prevent a child from accessing the needed conceptual systems.

In other cases, a child may be able to access a conceptual system but may have a different default bias for thinking about which system of expla-

nation is most relevant to the task at hand. A younger child may think hammers are used for hammering nails and not at first realize that they can also be used for sealing a paint can lid. When she realizes the relevance, she can use the tool immediately. The same pattern can happen with conceptual systems as tools. Shifting relevances in themselves may or may not be related to conceptual change. We have already seen how a child may undergo conceptual change in an area but still fall back on an older system because she doesn't fully realize the relevance or value of the new one. When the relevance is made clear, the child may suddenly use the system with ease.

One example occurs in the development of biological thought: younger children may interpret a property, such as "sleeps," in psychological terms and thereby judge that simple animals do not sleep (Carey, 1985). Yet when the same children are primed with a very brief context indicating that sleeping can also refer to how the body works, they will instantly attribute sleeping to a much broader array of cases (Gutheil, Vera, and Keil, 1998). The most relevant domain of explanation for a particular task may often come from experience with alternative framings or even from general cultural practices (Atran, Medin, and Ross, 2004).

It is therefore essential, when encountering developmental changes in children's ability to reason about various problems in the sciences, not only to understand the kind of conceptual change that is involved, but also to understand that some dramatic changes in performance ability may be largely unrelated to any underlying changes in conceptual understanding. As an adult, one can easily see how this is the case by considering how one's ability to understand a complex scientific phenomena may evaporate in the face of powerful cognitive distractions, massive sleep deprivation, or other factors that reduce the efficiency of cognitive processing. A sleep-deprived person hasn't really undergone regressive conceptual change; he simply has lost access and may not be tracking as well cues to the relevance of the best conceptual system. As mentioned earlier, however, memory and attentional changes can sometimes also be linked to conceptual change and, in such cases, bring conceptual change back into the process of developmental change.

CONCLUSIONS

As children enter elementary school, the pace of change in their knowledge and understanding of the natural world continues and sometimes seems to dramatically accelerate. Thus, while they bring much with them to the classroom from their preschool years, they launch into quite extraordinary expansions of their knowledge and understanding between kindergarten and grade 8. Understanding how their knowledge growth unfolds and can be supported requires an appreciation of the connections with earlier forms of understanding. Importantly, the kindergartener must be seen as far more than a bundle of mistaken ideas that needs to be completely reformed from scratch.

Admittedly, children's understandings of the world sometimes contradict scientific explanations, and these conceptions about the natural world can pose obstacles to learning science. However, their prior knowledge also offers leverage points that can be built on to develop their understanding of scientific concepts and their ability to engage in scientific investigations. Thus, children's prior knowledge must be taken into account in order to design instruction in strategic ways that capitalize on the leverage points and adequately address potential areas of misunderstanding. Young and novice students are likely to profit from study in areas in which their personal, prior experience with the natural world can be leveraged to connect with scientific ideas.

Debates remain about how the early understanding that children bring to school continues to develop across later years. According to one view, these core knowledge domains from infancy remain a nearly invariant framework of ways of understanding the world for much of one's life afterward (Carey and Spelke, 1996). Thus, even as adults, especially when under time pressure or distraction, we may show some of the same errors shown by infants in terms of their understandings of trajectories, collisions, and the like. By these accounts, there is a freezing of core knowledge domains early on because such knowledge can only be elaborated, not fundamentally revised. The later development of both naïve and more formal scientific theories depends on the ability to combine these domains (as well as other constructed understandings) in new ways, perhaps through language, which is said to have a kind of combinatorial glue-like power over these domains. These newer forms of knowledge, unlike core knowledge, are always open to revision, including quite radical forms of conceptual change. They also emerge in a different cognitive format and sit on top of these core domains but not really rewrite them or reinterpret them so much as coexist with them and be more evident when cognition is more reflective, slow, and considered.

An alternative view considers all knowledge to be revisable (Gopnik, 1996) and that these early domains continue to differentiate and become elaborated through childhood and perhaps into adulthood as well (Rogers and McClelland, 2004). For example, the folk sciences may start in infancy but continue to grow, as systems, for many years thereafter. In some accounts they may continue to gradually differentiate, but they always tend to have the same overall structure. In other accounts, quite dramatic patterns of conceptual change, sometimes akin to scientific revolutions in the history of science, are said to occur.

Conceptual change can take on several distinct forms, and the literature

uses several different senses of these kinds of change, sometimes not recognizing the differences (Inagaki and Hatano, 2002; Keil, 1999). It is critical to understand the full diversity of kinds of conceptual change and the range of mechanisms that bring it about as well as how developmental changes in scientific thought can occur without obvious conceptual change.

Some conceptual changes are more challenging than others. For example, when children develop commonsense frameworks that deviate substantially from those proposed by scientists, a considerable amount of conceptual work is required to achieve knowledge restructuring. Part of the difficulty of learning a new concept is letting go of a familiar but incorrect set of ideas. Major changes in conceptual frameworks are often difficult to grasp because they require learners to break out of their familiar frame and reorganize a body of knowledge, often in ways that draw on unfamiliar ideas. Making these changes is facilitated when students engage in metacognitively guided learning, when teachers use a variety of techniques (such as bridging analogies, thought experiments, and imagistic reasoning) to help students construct an understanding of new concepts, and when students have opportunities to strengthen their understanding of the new ideas through extended application and argumentation.

Importantly, the difference between students who are less or more proficient in science is not only that the latter know more discrete facts. Instead, gains in proficiency often consist of changes in the organization of knowledge, not just the accretion of more pieces of knowledge. When students develop a coherent understanding of the organizing principles of science, they are more likely to be able to apply their knowledge appropriately and will learn new, related material more effectively. Knowledge of the salient factual details is necessary but not sufficient for developing an understanding of the discipline and its core ideas and principles.

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